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DEEP SPACE COMMUNICATIONS

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ABSTRACT

This paper discusses the various factors that influenced the design of the TRACE deep space communications system, the choice of the operating frequency, and the selection of a suitable ground antenna. The configuration of the three different microwave communications system stations--launch, injection, and deep space--employed in the Pioneer III and IV experiments is given, together with a description of the computing and interstation communications system. A brief description of the performance of the TRACE system, its proposed development, and its future capabilities is also included.

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I. INTRODUCTION

In the spring of 1958 the Army was instructed by the Advanced Research Projects Agency to proceed on a lunar program consisting of two firings of a Juno II vehicle, the first firing to be before the end of 1958. The deep space communications for the Army's lunar program was designed, constructed, and operated within this time span by the Jet Propulsion Laboratory of the California Institute of Technology with major assistance from the Collins Radio Company and Blaw Knox Company, Equipment Division. The microwave communications system consisted of three different station configurations: launch, injection, and deep space, located respectively at the Atlantic Missile Range, Puerto Rico, and California. The basic design was code named TRACE (Tracking and Communications, Extraterrestrial). Performance was generally regarded as excellent, permitting good orbit determination and high-quality telemetering to greater-than-lunar distances. The telemetering contributed to the improved description of the inner Van Allen belt, materially contributed to the discovery and description of the outer belt, and for the first time transmitted information from deep space.

II. DESIGN CONSIDERATIONS

The total time available between initial design and operational status was less than 10 months. An appreciable capital investment was anticipated; consequently, an expendable-equipment philosophy could not be used. Because firing times were closely controlled by orbital considerations, it was important that the communications system be all-weather in order that vehicle firings would not be precluded by poor weather at the tracking and telemetering stations located around the world. Because it was virtually certain that deep space exploration would continue in the coming years, it was important that the basic design be commensurate with the projected state of the art, specifically with respect to parametric and maser amplifiers, increased power and efficiency in space vehicle transmitters, and future attitude-stabilized spacecraft. In addition, the limited number of firings in the program demanded that the communications system work reliably the first time and be relatively unaffected by large dispersions from the anticipated vehicle trajectory.

These design restrictions pointed toward an extrapolated Microlock system such as had been used in the Explorers, heavily modified by the design techniques used in the Army Corporal and Jupiter radio-guidance systems. It was evident that the Microlock frequency, 108 mc, was undesirable in the long run, that large tracking antennas would be required, that partially coded telemetering would be needed, and that a major effort in real-time computing and interstation communication would be necessary.

III. CHOICE OF FREQUENCY

The choice of 108 mc for the Explorer Microlock system had been made on the basis of compatibility with the Minitrack network established for the IGY. The Minitrack system had chosen this frequency for a variety of reasons, the principal ones being the availability of efficient and light-weight satellite transmitters, the desirability of using comparatively low gain ground antennas because of the anticipated satellite orbits, and the desirability of avoiding major ionospheric perturbations of the arriving signals. It was recognized, however, that 108 mc was a comparatively poor choice for deep space communications to be carried out in the 1960-1970 era, for the following reasons. Efficient vehicle transmitters were becoming available at higher frequencies. Large tracking antennas would be required for interplanetary communication. Since the angular motion of a deep space probe relative to a ground station more nearly resembles the motion of a star than a low-altitude satellite, pencil-beam ground antennas would be more practical for a space probe. Perhaps still more important, radio-astronomy evidence had shown that a quiet frequency region exists between approximately 500 and 5000 mc which could be exploited using parametric and maser amplification. The final choice of the TRACE communication frequency was based on the practicability of building a particular vehicle transmitter, on finding an appropriate large antenna, and on the availability of certain existing radio-guidance equipment which could be converted easily only to certain selected frequencies. The final choice was 960.05 mc. The vehicle transmitter problem was solved by L. R. Malling, who designed a transmitter which was completely transistorized with the exception of the final amplifier stage (Fig. 1). The ground receiver system (Fig. 2) was based upon the phase-locked-loop technique of coherent detection. It was constructed by modification of components of a previously proven JPL radio-guidance system. The original equipment had been fabricated for JPL by Motorola-Phoenix and was modified in part by the Collins Radio Company.

IV. CHOICE OF ANTENNAS

The choice of a ground antenna was made after a short but intensive study of the antennas which might be fully operational by the end of 1958, which could meet the stringent requirements for a high-quality parabolic surface, and which were operable in all-weather conditions, the major weather consideration being high wind. In addition, JPL desired that the resultant capital investment would meet the requirements of the anticipated space communications of the next few years. It was fortunate that a solution to the large antenna problem existed: an 85-ft-diameter, polar-mounted radio-astronomy antenna designed by Blaw Knox Company was available within 6 months at an established price. The significance of this set of circumstances can perhaps only be appreciated by readers familiar with large antennas. The design had been underway for more than 5 years, having been started at the Naval Research Laboratory, carried further at the Carnegie Institute, refined by the Associated Universities, and completed by the Blaw Knox Company just in time for the Army lunar program. On the other hand, although the design was complete, no antennas of this type had actually been constructed in the spring of 1958. In addition, the antenna was designed for a sidereal drive and not for automatic tracking. Fortunately, the areas of deficiency were those in which the considerable experience of JPL in Army radio-guidance systems could be used. The resulting station at Goldstone, California, is shown in Fig. 3.

V. THE NETWORK

Although the Goldstone deep space station was one of the more dramatic features of the program, it was equalled in importance by a much smaller station at the Atlantic Missile Range and by a mobile station at Puerto Rico (Fig. 4). The station at the Atlantic Missile Range received the signals from the TRACE vehicle transmitter during the very early portion of flight immediately after launch. One-way doppler information from this station was used to determine whether the launching had been successful. It also provided data to determine the approximate orbit, for use by the subsequent stations in acquiring the TRACE signal on their respective horizons. The Puerto Rico station, from the purely scientific point of view, was the most important station of the three. The Puerto Rico station first received the TRACE signal within 5 min after takeoff from the Atlantic Missile Range and maintained essentially continuous reception of the signal for the next 6 to 8 hr, until the deep space station in California first received the TRACE signal on the local horizon. During this period of time, while the probe was rapidly climbing away from the earth and apparently "circling" the Puerto Rico station, the probe passed through both Van Allen belts and began its journey into deep space.

The AMR station was a simplified version of the deep space station, consisting essentially of only the receiving channel coupled to a manually pointed parabolic antenna. The Puerto Rico station, on the other hand, represented a fully mobile version of the deep space station, with the modifications that its antenna diameter was appreciably less (10 ft instead of 85 ft) and that its servo system was a modified Nike I rather than a JPL deep space design.

VI. TELEMETERING SUBSYSTEM

The telemetering subsystem represented the least departure from previous space communications experience. The telemetering, a modulation on the 960.05-mc carrier, can be described as an IRIG/FM modulation system using very small modulation indices and detecting by linear, phase-locked-loop techniques. This telemetering subsystem design had been previously proven and was particularly applicable under conditions of signal variability due to spinning of the vehicle, unexpected attitude changes of the vehicle, and uncertain propagation conditions.

An interesting variation was used in coding one of the telemetering channels. Previous experience had shown difficulty in achieving sufficient dynamic range of the cosmic-ray measurements. The cosmic-ray instrument produced a series of pulses proportional to the cosmic-ray count. The cosmic-ray count could change over a ratio of 2500 to 1; yet it was important to have data of approximately 10% accuracy, regardless of the absolute count. This problem was solved by taking a series of taps from a scaler, each tap representing successively larger counts per output pulse. The output from each of the taps was set at different voltage levels, was passed through a low-pass filter, and the sum was applied to a subcarrier (Fig. 5). The resultant effect is approximately illustrated in Fig. 6. This particular coding method proved outstandingly successful in the accurate exploration of the Van Allen belts. A short period of Pioneer III telemetering data is shown in Fig. 7. In other respects, the telemetering and recording display system was essentially the same as the JPL FM/FM system originally developed in conjunction with the Army Corporal program.

VII. COMPUTING AND INTERSTATION COMMUNICATIONS

The real-time computing and interstation communication system was almost completely new with respect to previous JPL programs, although the general techniques were well within the state of the art. Velocity and angle information from the tracking site was digitalized, converted to a standard teletype format, and relayed to JPL in Pasadena. There it was used in an IBM 704 to calculate the probe's trajectory and to derive pointing information for signal acquisition by the tracking stations. The computer programming performed a root-mean-square fit of all available tracking data from which best estimates of the injection parameters of the orbit were determined: velocity, position, and angular coordinates of the initial point on the free-flight trajectory. Using these parameters, the complete orbit was calculated, and the acquisition information required by the tracking station was subsequently derived. The success of the technique depended upon the fact that free-flight in the vacuum of space is virtually devoid of unknown disturbances. In this respect, deep space flight is significantly different from satellite flight in the near vicinity of the earth or missile flight within the sensible atmosphere.

In addition, in the computer programming it was assumed that certain types of errors existed at the various tracking stations, errors such as angular bias in the angular tracking system, frequency shifting of the crystal-controlled oscillator in the probe, and frequency shifting in the ground station reference frequencies. As part of the computing operation, the computer solved for these errors at the same time that it computed the orbits. Because of the tremendous amount of tracking data available, it was possible to compute an orbit far more accurate than the instantaneous pointing ability of any one tracking site. The orbit determined by the computing operations could be demonstrated to be better than 0.2 mrad in accuracy, although the tracking accuracy of Puerto Rico was certainly not better than 8 mrad and that of Goldstone, 2 mrad. Given this computed orbit as a standard for comparison, the instantaneous tracking accuracy of the various stations could then be estimated.

VIII. OTHER STATIONS

Several other stations participated in the Army lunar program on a less formal basis. Several of the Army Microlock stations located on the East Coast of the United States were converted to 960-mc reception to perform an evaluation of the vehicle launching process similar to that performed using the Microlock on the Explorers. These stations, under the direction of the Army Ballistic Missile Agency, closely resemble the JPL launch station in complexity and in recording equipment. The Microlock equipment at Jodrell Bank, installed by the Air Force for its lunar program, was converted by the Air Force to 960 mc to permit reception of signals from the Army probe. The manually positioned Jodrell Bank antenna was most useful at the greater distances when the angular rates were low and the angular position well known. Various other stations listened to the 960-mc transmission from the probe on a still less formal basis. The performance of one of these stations, a station established by the General Electric Company, is reported elsewhere in this issue.

IX. PERFORMANCE

Pioneer III was launched on December 6, 1958, and reached an altitude of 63,500 mi, after which it returned to the earth in the vicinity of Central Africa During the time of flight the projected point on the earth immediately under the probe travelled from the Atlantic Missile Range to West Central Africa, at which point it "reversed" across the Central Atlantic, South America, the Pacific Ocean, the Indian Ocean, and finally Central Africa. During the flight, approximately 24 hr of radio contact were maintained, 14 hr of which were by Puerto Rico and 10 hr by the Goldstone Deep Space Net Station. The Puerto Rico station showed an ability to obtain usable telemetering to distances in excess of 40,000 mi; the California Deep Space Station, because of its appreciably larger antenna, obtained very strong signals throughout its tracking period. The Puerto Rico station obtained excellent telemetering data on both the rising and falling legs of the flight and consequently was twice able to provide a high-quality description of the Van Allen radiation belts. Operation of all stations and of the vehicle transmitter was well within tolerance. The received signal strength was 3 to 4 db less than expected because the spin axis of the probe had been cocked by a launching vehicle disturbance.

Pioneer IV was launched on March 3, 1959, passed the moon at a distance of 37,300 mi southeast of the moon, and then continued on to become a planet of the solar system. The projected point on the surface of the earth immediately below the probe was similar to that of Pioneer III with the exception that the sub probe point continued circling the earth rather than ending in Central South Africa. Tracking and telemetering performance of the TRACE system for the first 100,000 mi of flight of the probe was closely similar to the first portion of the Pioneer III flight with one exception. A deviation from the standard trajectory caused the probe to dip below the eastern horizon from the Puerto Rico station for a period of 30 min; consequently, signal information was lost during that time. Reacquisition by Puerto Rico and all subsequent acquisitions by Goldstone were normal. The Goldstone station first acquired the probe signal 6.5 hr after launch when the Pioneer IV was 60,000 mi from the earth. For 15 min, four tracking stations, AMR, Puerto Rico, California, and England, were all locked onto the Pioneer IV transmission. A unique opportunity was thus provided to obtain a four-way fix on the probe to the exact position in space. Goldstone then maintained contact for almost 10 hr until the earth's rotation caused the probe to descend below the horizon. Goldstone was then able to obtain an additional 10 hr of tracking per day for March 4 and 5, 1959. On March 6, Goldstone made its fourth and final acquisition at a range of 399,000 mi. Loss of the signal occurred during this tracking period when the probe's batteries became exhausted. The range at this time was 435,000 mi. Telemetering quality was still high and no difficulty was being experienced in velocity or angle tracking. The TRACE system had therefore met its design goal of providing high-quality space communications to the distance of the moon and beyond. Had more battery life been provided (at a considerable cost in weight), the TRACE system could have maintained useful contact for about three times as long in both time and distance. The use of parametric amplifiers, excluded from the initial receiver because they had not yet been system proven, would have doubled system performance.

X. THE IMMEDIATE FUTURE

The long-term capability of the deep space net is summarized in Table 1 for the period of 1960 to 1964. The addition of ground transmitters will be noted, an addition which makes possible accurate two-way doppler, accurate ranging, and ground-to-probe command. The increase in spacecraft antenna gain is the result of the use of stabilized vehicles. The decrease in the effective temperature of the ground and spacecraft receiving systems is due to the incorporation of parametric amplifiers. Otherwise, the major elements of the TRACE system, the antennas, the tracking equipment, etc., continue to be used during this period.

Present plans also call for the installation of two more deep space stations spaced at approximately 120 deg in longitude around the earth. This will permit continuous contact with a deep space probe during its journey to the moon or the planets.

TABLE 1. LONG-TERM CAPABILITY OF THE DEEP SPACE NET
(Predicted Schedule)

Characteristic	1960	1962	1964
Transmitter Power			
Ground	10 kw	10 kw	10 kw
Spacecraft	10 w	25 w	100 w
Antenna Gain			
Ground	46 db	46 db	54 db
Spacecraft	6 db	20 db	30 db
Receiver Sensitivity			
Ground	300°K	100°K	40°K
Spacecraft	2000°K	2000°K	400°K
Information Bandwidth-Telemetry (10 db S/N)			
Satellite Application	3.5 kc	1 mc	1-10 mc
Lunar Application	3.5 kc	1 mc	1-10 mc
Mars Application		100 cps, 18 db S/N	10 kc
Venus Application		400 cps, 18 db S/N	40 kc
Edge of Solar System			10 cps

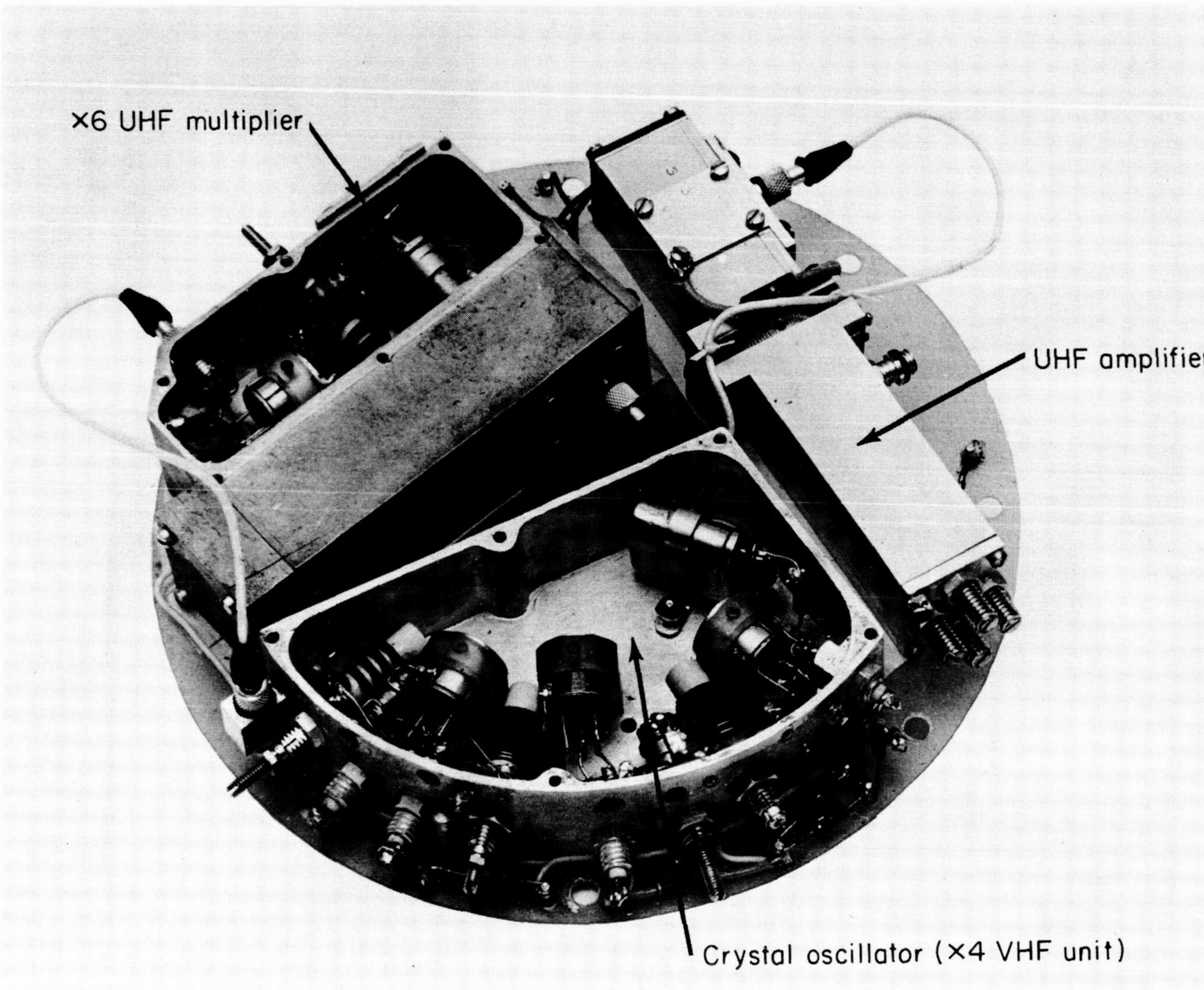

Fig. 1. Lunar Probe Transmitter, Development Model

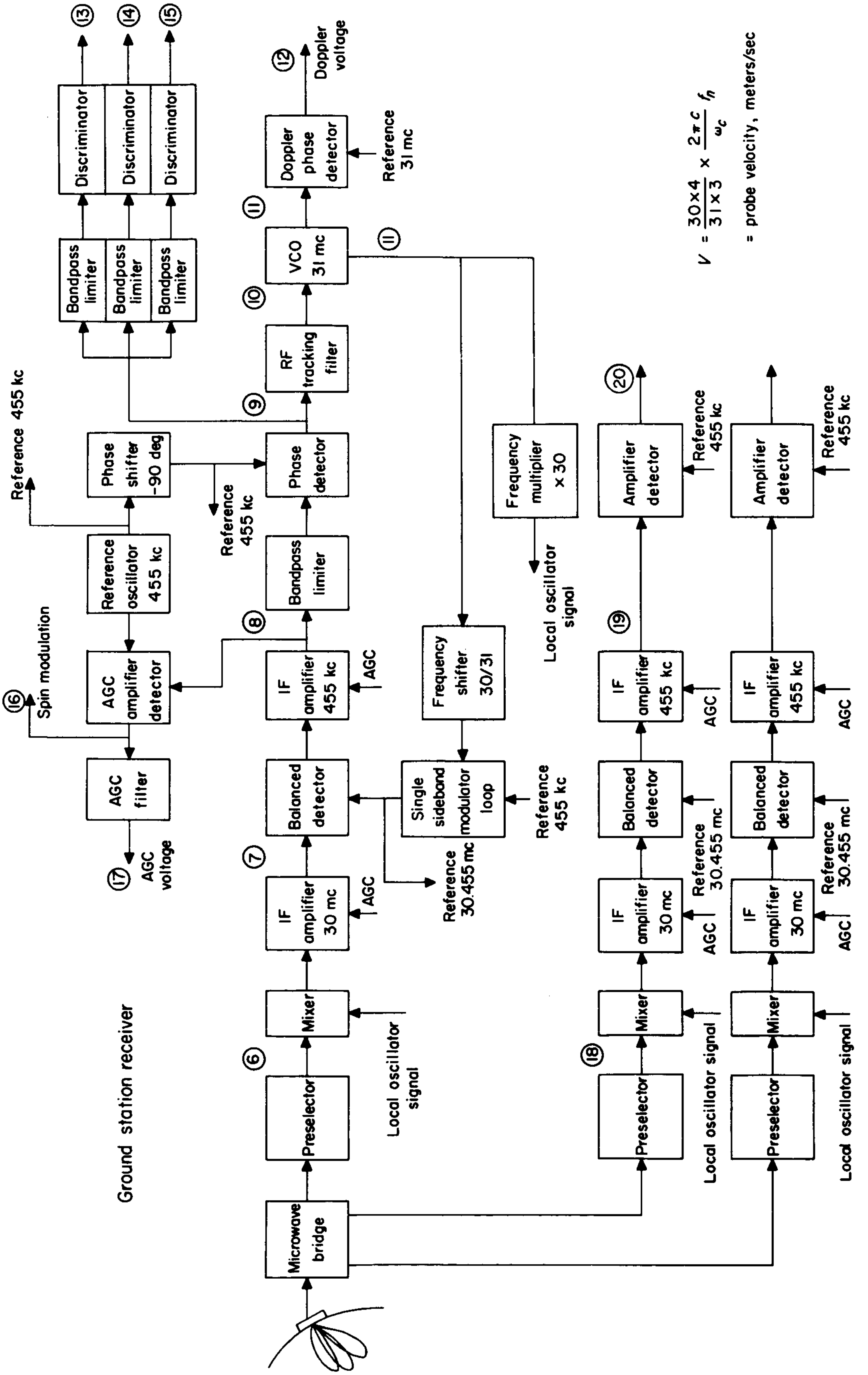

Fig. 2. TRACE System for Goldstone Tracking Station

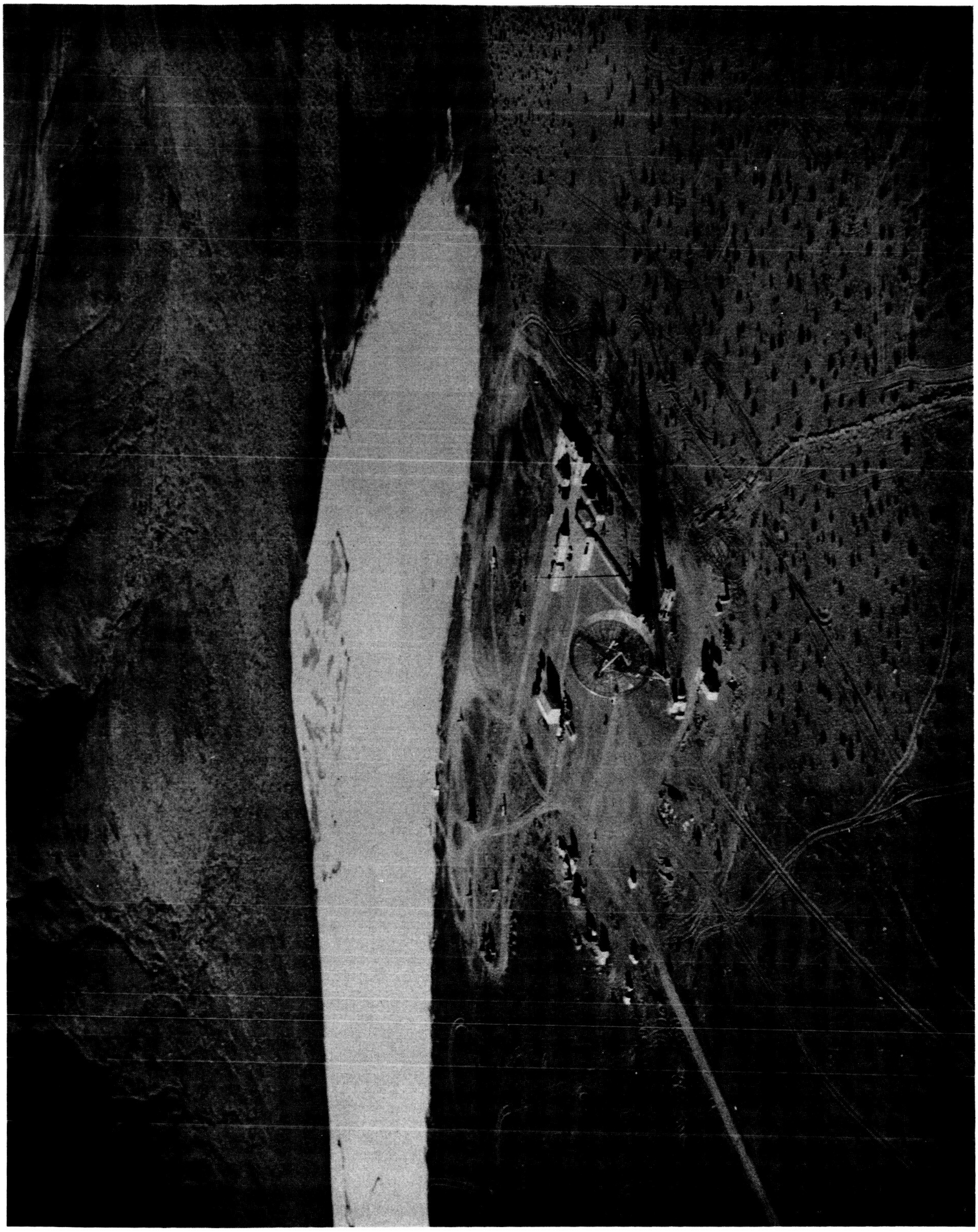

Fig. 3. Goldstone Deep Space Station

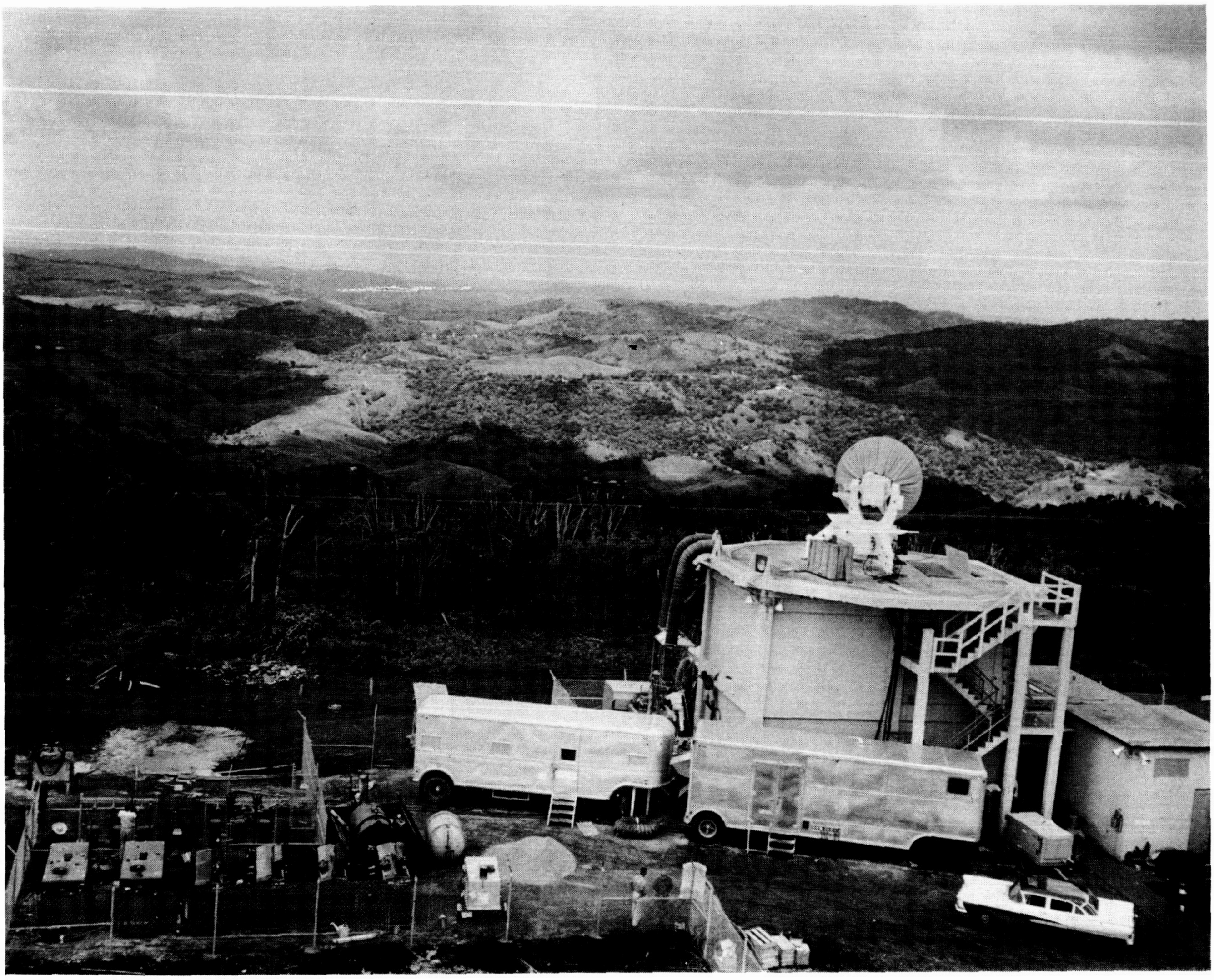

Fig. 4. Puerto Rico Tracking Station

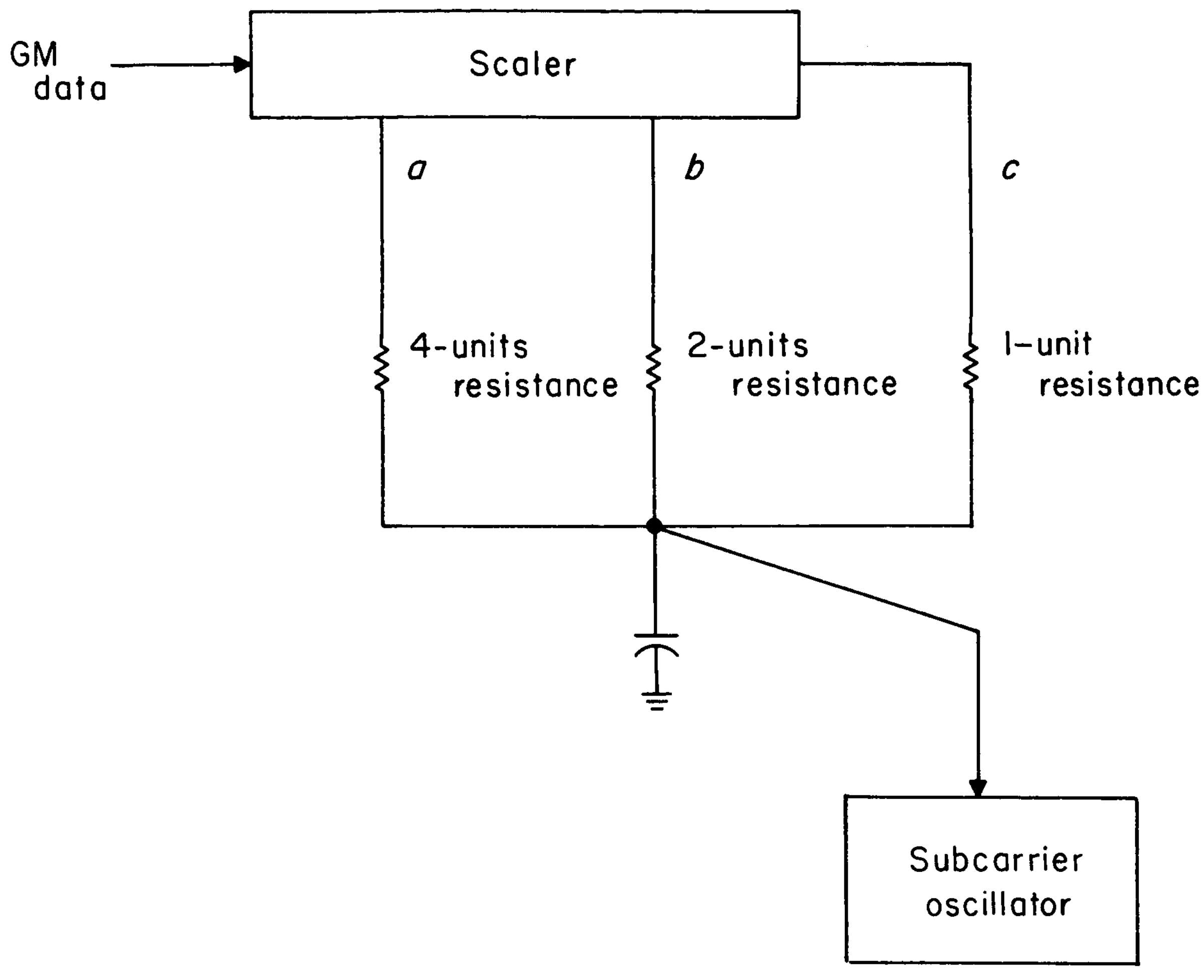

Fig. 5. Weighted Mixing Circuit Planned for Soft Radiation Experiment

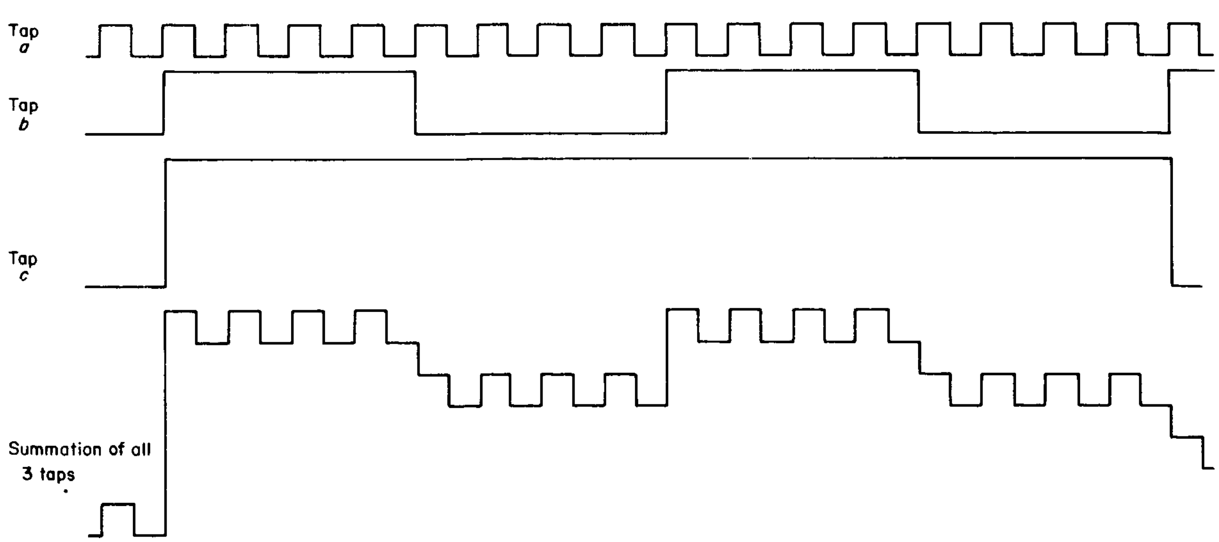

Fig. 6. Individual and Mixed Wave Forms

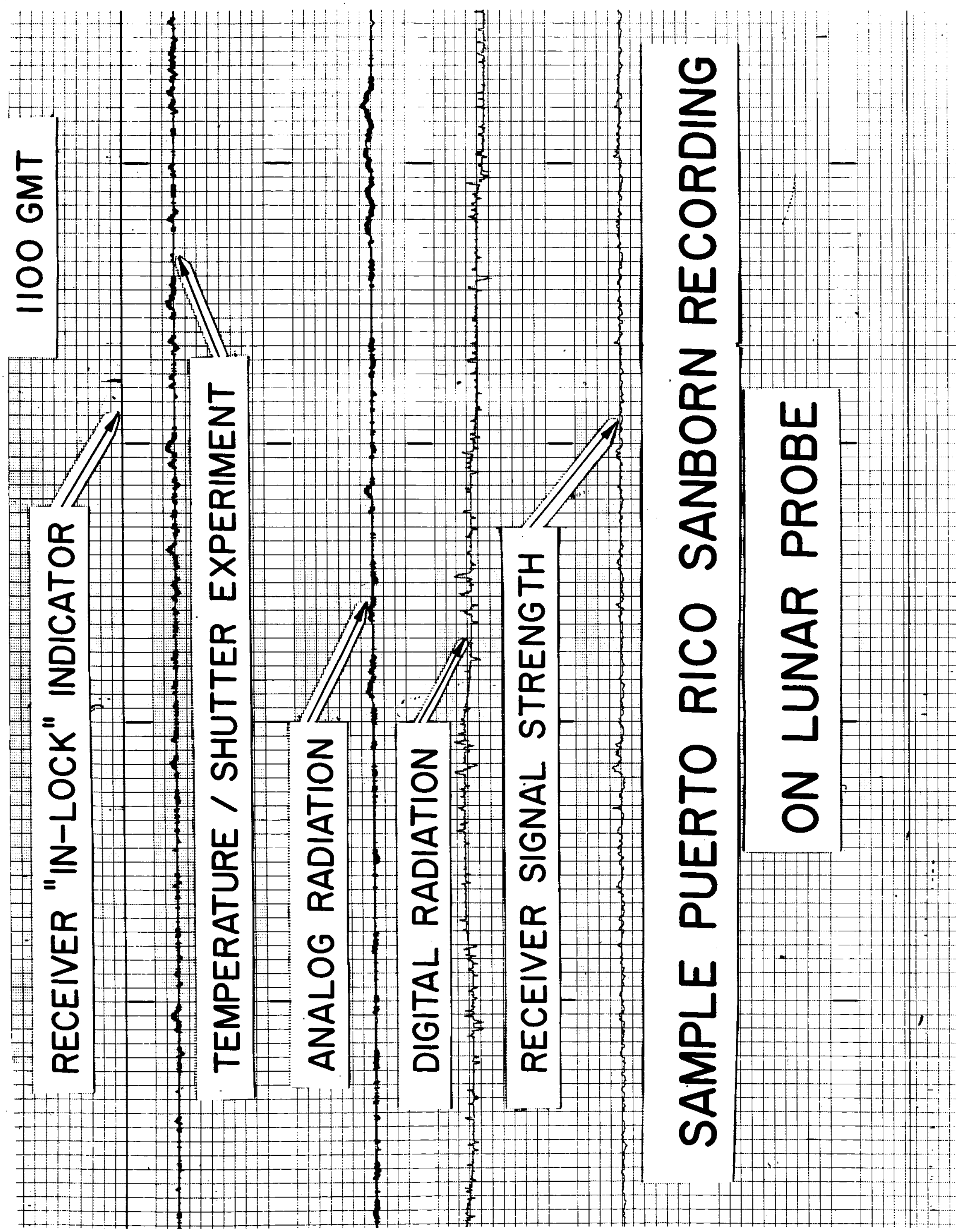

Fig. 7. Pioneer III Telemetering Data